Numerical simulation of turbulent flows in natural systems: Framework

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A convergence of a number of factors has now led for a significant and major step forward towards filling a central and common lacuna in the areas of climate prediction, energy generation due to tidal power, prediction of natural disasters such as floods arising due to modification of ocean circulation in sub-surface flows.

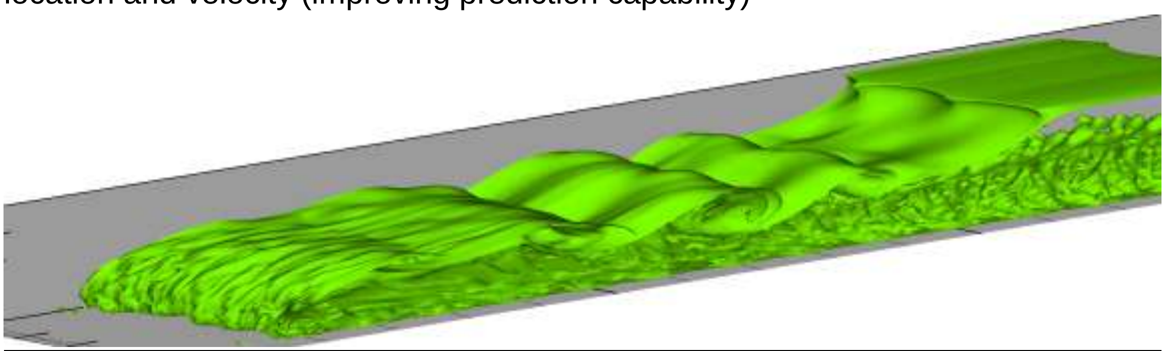
One of the primary lacunas in climate prediction is the characterization of turbulent boundary layer due to the presence of urban roughness (man-made structures such as buildings) as well as natural vegetation (trees and forests). In the area of ocean flows, the flow over rough ocean bed consisting of sediments, ripples, which constitutes the bedform dynamics, is major source of energy dissipation of water waves outside the surf region (e.g., Ardhuin et al. 2002). Accurate prediction of coastal hydrodynamics which is of critical importance for the prediction of natural disasters depends on understanding and realistic parameterization of bottom boundary layer processes (e.g., Grant and Madsen 1979; Mathisen and Madsen 1996). Some of the fundamental questions regarding turbulent boundary layer over these bedforms are still unanswered. Tidal power is one of the prospective areas for the alternate energy generations and the modification of circulation currents which determine the amount of energy generated due to the placement of turbines is dependent on accurate characterization of flow around these turbines. The common lacuna of all these systems is the lack of accurate characterization of turbulent flow due to the presence of these complex surfaces (i.e. how the presence of urban roughness (complex surface) alters the turbulent flow close to land, or rough-ocean bed or the presence of ripples modify the flow in that region).

The factors which will make it feasible for an accurate characterization of turbulent flow over these complex surfaces are - (a) the next generation computing systems which will make it feasible to stretch the Reynolds number/roughness scale limitations of flow computations and perform large scale simulations, (b) development of robust numerical tool for the accurate simulation of turbulent flow over complex boundaries with a capability of large-scale simulations, (c) development of novel analytical tools very specific for complex surfaces to synthesize the vast numerical data generated from these simulations and to provide meaningful interpretation of the flow physics.

A good starting point for analyzing the turbulent flow over complex surfaces is formulating a set of averaged Navier-Stokes and turbulent stress transport equations, which fully reflect the arbitrarily rough boundary, via a Favre- or multi-phase averaging approach. This approach will result in explicit roughness drag and turbulence production due to roughness in the momentum and TKE balance equations respectively. Further, scalings or parameterization for roughness induced drag and turbulence production needs to be developed. This strategy for this has two elements: This first is the formulation of a useful functional form for the drag term, reflecting the varied geometry and the local flow fields at the wall. The second element of formulating a drag model is the calibration of the drag model at the local level via DNS experiments.

DNS has been performed for the following systems:

(a) Coastal Systems: DNS tool was used to study sediment transport over 2-D and 3–D bedforms by Bhaganagar and Hsu (2009, 2010, 2011). Some fundamental questions that need to be understood: (i) What is effect of surface irregularities in altering the mixing or entrainment of the flow (ii) what factors effect the front location and velocity (improving prediction capability)



The density currents generated through lock-exchange mechanism over a rough surface showing the classical Kelvin-Helmholtz instability (shear roll up) and the lobe-cleft instability (spanwise).

(b) Wind Turbine Farm simulation: Several important unanswered research questions that stem directly from our current understanding:

(i) What are the possible two-way couplings between a large wind farm and the atmospheric turbulent boundary layer, and how does local weather and climate affect wind farm operation, and vice-versa?

(ii) How does the variable intermittent turbulent inlet flow influence the power output of the wind farm and how does this accumulation of additional wake turbulence affect the downstream wind turbines and their operation?

(iii) How do different wind turbine layouts affect the power output generated by the wind farm, specifically as one changes the rotor design and how does one optimize the entire power/economics of the wind farm?

(iv) How do uncertainties from a single turbine propagate over the entire wind farm system, and subsequently into the electric grid and cost of energy?